6-2012

Coupling of Audio Signals into AFM Images

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By

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Submitted in partial fulfillment
of the requirements for
Honors in the Department of Electrical and Computer Engineering

Union College
June 2012

Foreword

MANNING, MATTHEW Coupling of Audio Signals with AFM (Atomic Force Microscope) Images. Department of Electrical and Computer Engineering, June 2012.

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It is well known that Atomic Force Microscopy imaging is capable of yielding high resolution results with of surfaces at the nanoscale. However, despite the device capabilities and vast applications, AFM microscopy is possibly the most prone to the creation of image artifacts. AFM imaging can easily, and is often, corrupted by various external forces. The most obvious and measurable form of external interference is of course the presence of ambient noise. Most AFM manufactures attempt to counter the effects of such noise on the imaging process through use of noise-proof or noise-resistant shields that cover the microscope aperture. Without such shields however, the effects of ambient noise are distributed throughout the resultant image. Furthermore, the detection and interpretation of AFM errors is still a quite muddled procedure.

The goal of this research project is to delve underneath the hood of an atomic force microscope and investigate the nature of errors caused by ambient noise on the imaging process. Through this investigation and the use of digital signal processing I hope to accurately identify the resultant artifacts left on an AFM image over a range incident signals. Having this knowledge is the first step towards several practical applications:

- Accurate detection and interpretation of image errors
- Better preventative measures or extraction techniques of errors
- Development of method by which AFM may be used as a physical recording medium

Summary

The main approach to this investigation of audio induced image errors was to first determine the system response of the AFM in the three main modes of operation; attractive, repulsive and intermittent contact modes. The comparison of impulse responses of the three modes confirmed the nonlinear nature of the AFM system as defined by the general force-distance curve as seen in **Appendix A.** However, the extent of the nonlinearity raises many questions as to the proper interpretation of errors in different modes.

Through excitation of the system with sinusoidal, I discovered that sinusoidal incident signals result in sinusoidal image errors, although aliasing was observed. The attempted recovery of complex music signals resulted in a basic proof of concept that a similar system could be developed for use as a recording method; however a typical AFM has certain constraints that prevented the desired results.

Table of Contents:

Table of Figures

Introduction:

Atomic force microscopy, commonly referred to as AFM, is an extremely precise and versatile tool in the measuring and characterization of surface topography at the micro and nano-scale. Through utilization of the various operating modes of the AFM, one is capable of measuring conductive and non-conductive samples, as well as hard and soft samples. This diversity extends the usefulness of the device from material engineering to the biological study of living cells and everywhere in between. When utilized properly, AFM imaging yields unprecedented resolution and accuracy that can show the arrangement of individual molecules or even atoms in a sample.

Atomic force microscopes are quite unlike optical or electron microscopes in that they do not rely on the focusing of light or back-scattered electrons to image a sample. Rather, AFMs rely on an extremely sharp probe that physically “feels” or senses the surface of a sample. This direct interaction with the material surface is what yields such exact measurements of topographical information that cannot be obtained through optical or SEM observations. However, although AFM imaging can be incredibly precise, it does not come without flaws.

In the oscillating modes, the AFM relies on atomic forces between the probe tip and the sample surface to maintain a desired average distance between the probe and the sample surface. Changes in the voltage required to maintain the desired distance are measured by the reflection of a laser onto a photosensitive detector and then converted into topographical information. Since the accuracy of these modes are heavily dependent on such small forces, the resultant image may be easily affected through external electromagnetic forces, surface charge of a material, or more importantly to this project, the presence of ambient noise during the imaging process.

Although the easiest way to counter the appearance of artifacts is by imaging in a noise free environment, this is often easier said than done. Completely noise free labs cost millions of dollars to construct and thus are typically available in commercial research institutions or universities with PhD programs; i.e. not Union College. For this reason, the event of error due to ambient noise is almost implied when imaging under non-ideal conditions and the burden of determining between corrupt and acceptable images lies solely on the observations and judgments of the image taker. The goal of this project is to provide a “second opinion” as to the authenticity of AFM image results through error characterization. If error may be automatically detected or possibly even corrected through a digital signal processing method, one can easily avoid wasting valuable time analyzing corrupt results.

Project Objectives

The main goal of this project is to begin a thorough investigation of the effects of audio signals on the AFM imaging process. I aim to compare image errors causes by like signals in three different modes of operation; attractive, repulsive and intermittent tapping modes. This will be done through the following steps:

- Development of audio signal delivery system
- Selection of several useful incident signals to introduce to the system
- Using the line-out of AFM images to compare results
- Attempting the recovery of incident audio signals through digital signal processing

Experimental Methodology

For the purpose of identifying and characterizing the artifacts left by ambient noise in AFM images, the experimental methodology is quite simple; image the same sample and sample area multiple times, both with and without the presence of noise, and in various operating modes. The images taken without the presence of noise, or rather with minimal noise, will represent the control or reference conditions. Conversely, the images taken under the presence of noise will represent the experimental conditions. Comparison between the two through digital signal processing will serve as the method by which I am able to identify the effects of audio signals on the resultant images. The same methodology will be employed for a variety of incident signals; single frequencies, multiple frequencies, impulses and white noise. The intelligent design of such incident signals will play a large role in the overall effectiveness of the investigation.

I will begin the investigation by first introducing the system to impulse-like noise. If the AFM works as a linear system, then the response to these near impulses should be representative of the system response. However, all AFM users should be aware of the general force distance curve shown in **Appendix A**. According to this graph, as the average distance of the cantilever from the sample surface changes, so too does the force exerted on the cantilever by the sample surface and as one can clearly see, the relationship is not linear. Despite this fact, most AFM users do not pay much attention to this relationship and switch freely between modes. The results of this investigation will tell us whether or not this carelessness is actually within reason or if the movement along the force-distance curve in **Appendix A** has a significant effect on resulting images.

Background:

The best approach in the development of any research project is to learn from the results of similar or related projects that have been conducted in the past. As this particular project is a marriage of concepts from several distinct fields the required background knowledge is quite diverse. The following sections will assist in the understanding previous of works and general applications that contribute greatly to the design and experimental approach that should be taken for the task of extracting and lithographing features related to ambient noise error in atomic force microscopy image.

AFM Data Storage

Although this project will not likely end up with a convenient or even practical form of data storage, there certainly have been serious attempts to utilize AFM reading and writing as precisely that. "The Millipede Project," is one such example in which highly modified AFM apertures were used to read and write information on specialized polymer substrates. This data storage system relied on an array of 4096 heated probe tips that interacted with the storage medium. The heated silicon tips were able to completely evaporate the storage material where desired, due to intelligent design of the writing medium. This entirely eliminated a major concern that I will likely encounter with my project, where excess material left behind from the lithography will distort the results of the signal processing system.

The Millipede Project was conducted at IBM Zurich Research Lab from 1998 until 2006. The fact of the matter is, however, that the reading and writing capabilities of the device could not compete commercially with other data storage systems such as Flash. This is not to say that the research was not successful however. The Millipede system at its peak performance was capable of storing approximately 1Tb/sq in. Additionally, it opened the door for many new applications for atomic force microscopy aside from basic imaging. Being that was is a highly funded and almost decade long professional research project there is much to learn from studying its design and development, and if nothing else it is an irrefutable proof of concept for using AFM image information as data storage. [1]

Surface Topology as Sound Interpretation

Another key component of this project is not only the scaling down factor that AFM provides in terms of data storage area, but also the way in which this data is read and interpreted. Probably, since the invention of the first wind up music box, people have been utilizing surface topography of various materials and forms to represent data or audio information. Other examples range from player pianos, classic vinyl and wax cylinders. The main difference between the method in which I intend to read such information and the way most other data storage systems read topographical information is that I will be doing so without contact through imaging in an oscillating mode. This idea is paralleled by the work of Vitaliy Fadeyev and Carl Haber at the Lawrence Berkeley National Laboratory, in which they are utilizing non-contact optical surface metrology to read audio information.

The “mechanical carriers” utilized in this study were wax cylinders for use in an Edison phonograph. A phonograph works based on the principle of using wavy grooves in the cylinder surface to physically induce vibrations in a needle or stylus. As the preservation of recorded sound is coming of higher interest as such mediums degrade over time, a method of reading the engraved information without physical manipulation would be of great value to the effort. Vitaliy Fadeyev and Carl Haber have developed exactly such a method using advanced CCD cameras to reconstruct three-dimensional representations of mechanical audio carrier surfaces. The 3D images are collected from rotating the mediums and with no physical contact that may wear the delicate materials. These images are then able to be processed digitally and successfully extract the imprinted audio information [2].

Capabilities of AFM Lithography

Another differentiating feature between atomic force microscopy and optical or electron based microscopy methods, is the ability to not only take measurements and images, but also, manipulate sample surfaces. Although the creation of complex nano-structures is possible with AFM techniques, most require additional preparation such as chemical masks or salinization. More standard techniques such as scratching, plowing, local and the “dip-pen” methods are somewhat limiting in the nature of structures one may produce, however, they are much easier to execute and take little time in comparison to more complex techniques.

Scratching and plowing are among the simplest methods both conceptually and in terms of execution. Both rely on driving the probe tip at higher set voltages than typically used for imaging, thus causing the tip to penetrate the sample surface. When scratching the tip is simply dragged along a predetermined trace line, resulting grooved structures. Plowing is slightly more advanced in that rather than dragging the probe tip it oscillates according to a desired force map and chips the sample surface.

The dip-pen method is slightly more complicated and advertently more versatile than the aforementioned methods. The concept of this method truly does parallel that of a microscopic pen, in that it uses the AFM probe tip to deposit a desired material onto the surface of another. This method has many applications since it is able to construct features of differing chemical components, something that is highly desirable for the construction of diode or transistors for instance. Although this method is quite simple to execute as well, it does require hydrophilic tips in order to deposit aqueous solutions and is something that should be considered in the design of this project [3].

AFM Image Processing

Due to the high influence of small exterior forces on the AFM imaging process, image artifacts are extremely common. Although reimaging may be the best way to avoid such inconsistencies, image processing is becoming an increasingly popular and convenient way to eliminate error and save valuable time. John Russ, author of the Image Processing Handbook, emphasizes that image processing is an incredibly useful tool as long as the results stay true to certain scientific standards. A common mistake that I will likely encounter in my project will spawn from the fact that I already know the frequency content of the error causing noise. This knowledge is obviously crucial to the justification of the completed processing system, yet I must avoid its influence the design process. I aim to create a method capable of detecting a wide range of frequencies not a single incident signal. Although the detection of any frequency will be viewed as a success to some degree, single frequency information would be essentially useless to the average project.

Russ outlines and describes many techniques deemed acceptable for use in AFM image processing. These techniques include leveling, plane fitting, filtering, scaling, and error correction. Leveling and plane fitting are luckily already done within the software of our AFM, although the parameters of these functions may be adjusted if desired. Typical filtering and error correction processes both address the same concern as this project, that is, the elimination of unwanted frequency content. However, my goal is not to simply eliminate this information, but rather to identify it for use in elimination at the source within the lab, or to justify whether its impact on an image is within an acceptable range for scientific purposes. Finally, scaling will likely be a useful tool, as long as the effects of ambient noise cause error that are of a magnitude greater than the average variance of the sample surface magnitude [4].

Design Specifications:

In this section I will outline the key design components which were considered in the design and development of the project. These requirements will outline the intended operation and desired results that are expected from successful implementation. It is by this outline that the overall quality of the project results is to be determined. By meeting the specifications of each individual project component, a successful, coherent system should result.

Error Characterization:

Incident Signal

The main concern for the error characterization section of this project is not a question of whether or not ambient noise dose have an effect on imaging, but rather, what form do the error artifacts take in a corrupted image? In order to determine the answer to this vital question, the design of my experimental incident signals is of paramount importance. Preliminary laboratory tests, which consisted of yelling, singing or clapping near the microscope aperture, have irrefutably proven that these occurrences adversely affect the final image. However, these results are far from credible in that the frequency information of such improvised signals is quite unpredictable and hardly regular.

Taking into consideration what is required of useful incident signals I have composed the following design requirements:

- Easily modeled
- Consistently reproducible
- Avoids frequency of probe cantilever
- Avoids frequency content of sample surface characteristics

Having an easily modeled signal will make for easier detection in the initial development stages. A more complex signal model would be more difficult to identify and extract given it would require a higher number of identifying parameters. Reproducibility is quite obviously important in order to maintain consistency among experimental samples. Avoiding an incident signal which consists of the resonance frequency of the cantilever will prevent over-stimulation of the cantilever, likely resulting in breaking. Finally, avoiding the frequency content inherent to the sample surface will make it difficult for the effect of error to be masked by the natural characteristics of the experimental samples.

Sample Material

Selecting an optimal experimental sample material for this project will make for much ease in the design on the incident signals as well as less complexity in the signal processing method. The specifications for an ideal sample material are outlined as follows:

- Uniform surface characteristics
- Ideally, completely flat
- Capable of being lithographed

Having a uniform or ideally flat surface (several nm fluctuations) greatly broadens the possibilities for the design of incident signals. Should a sample surface be completely flat, its inherent frequency content would be 0 Hz and thus any frequency of ambient noise should be easily apparent upon imaging. Additionally, having a flat sample surface is essentially a blank canvas when it comes to attempting any sort of nano-lithography which may be utilized in the future development of a physical recording method. Attempting to lithograph on a highly differentiating sample surface would be far too complex.

Probe Tip Selection

Just as there are many different modes of operation for atomic force microscopes, there are just as many if not more kinds of probe tips specific to particular applications. Since this project will rely on the comparison of results in different operating modes, the selection of an optimal tip is not an exact science. The chosen tip model should meet the following requirements:

- Operates effectively in tapping mode for precise imaging needs
- Operates effectively in contact mode for lithographic needs
- Durable
- Cost effective
- Resonance frequency out of audible range

As previously discussed, the probes that will be utilized for this project must be capable of both contact and non-contact operation. Additionally, as I must budget expenses according to the money granted by the Internal Education Fund, the selected tips must be both durable and cost effective. Finally, by choosing a tip which does not have a resonance frequency within the audible range (over 22 kHz) the design of experimental incident signals is not likely to be affected.

Digital Signal Processing Method:

Once both control and experimental images are appropriately gathered, it is up to the designed digital signal processing method to compare the images and decipher error. This sort of error extraction will result in a pictorial template by which the effects of error can be identified for various incident signals. The processing method will follow the following general approach:

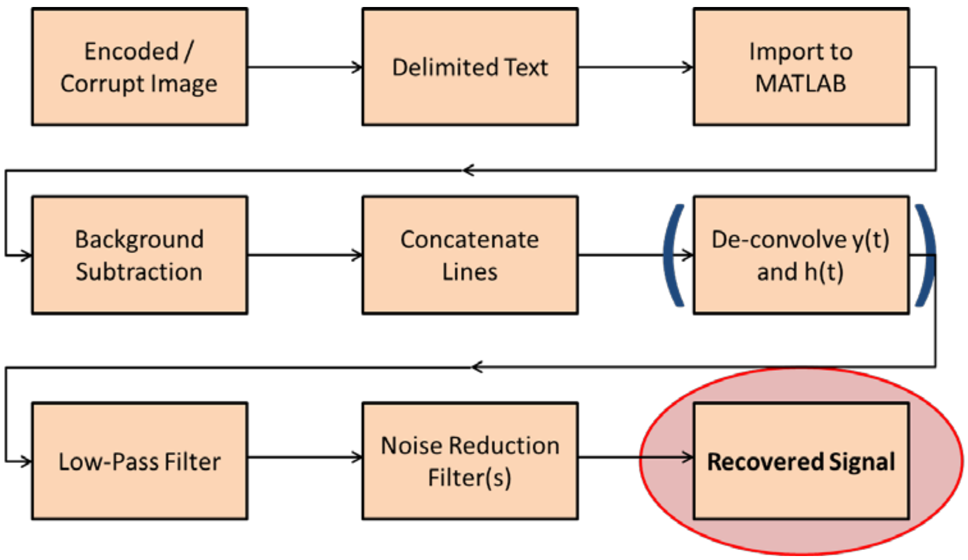


Figure 1: Signal Processing Approach

The file format of images produced by the AFM is a proprietary format called Igor Binary Wave or .ibw. The first step in the data processing will be to convert these proprietary formatted files into another form which can be imported into a program capable of signal processing, likely to be MATLAB. It is important that during this step no valuable image information is lost that may distort the final results; however there is other information which may be better off left out. For instance, data pertaining to the operating parameters of the microscope while imaging will be identical for each image and thus irrelevant for the purpose of image comparison.

When data is formatted into a useable form, the image information of the corrupted images will be compared to reference images via background subtraction. The image data will be arranged back into a single line array to be interpreted as audio information. This array will then be subjected to a series of filters and other manipulations aimed at the recovery of the original incident signal. The result of this process should yield the true disturbance caused by the various incident signals. This information is what will allow me to correlate image artifacts into frequency information and ultimately extract the effects of error in the form of the original incident signals. Successful correlation of errors to audio information in various modes could be used to assist researchers in the authenticating of results or help to pinpoint the source of such ambient noise error in the lab so that it may be removed.

Preliminary Design:

Experimental Setup

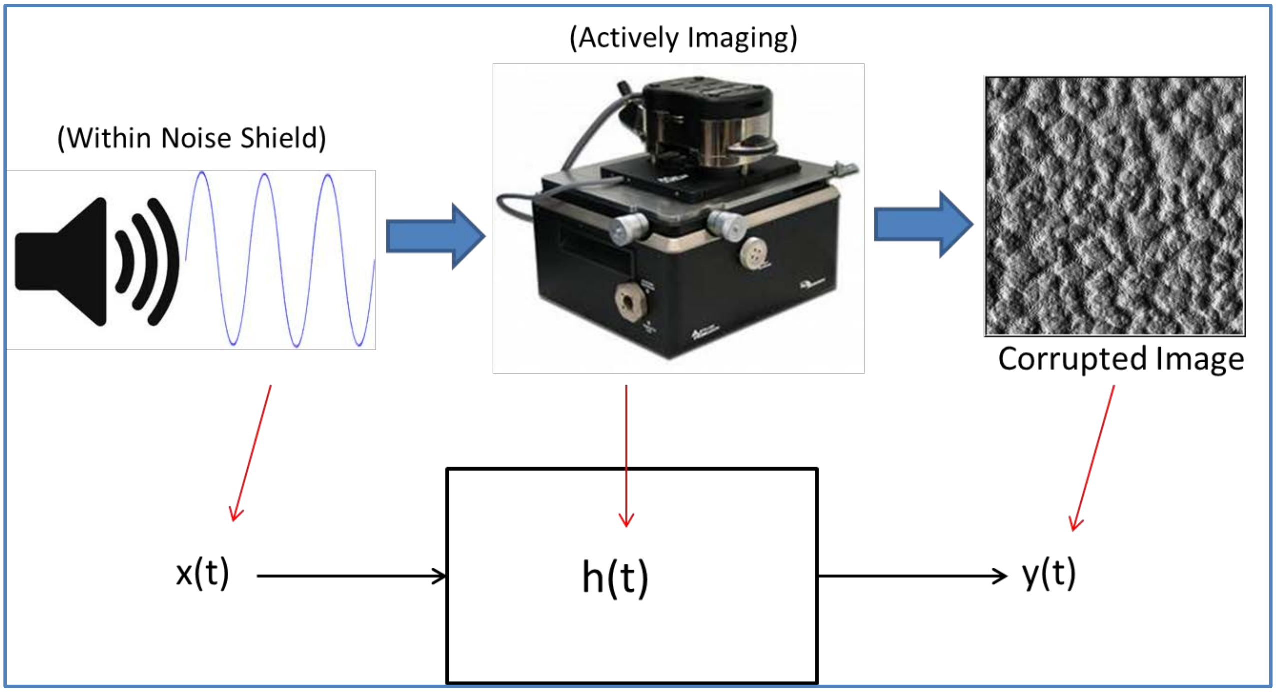


Figure 2: Experimental Setup

The experimental setup of this project is quite simple. The goal is to introduce various incident signals it to AFM imaging process. I plan to do so by placing a small audio speaker inside of the closed noise shield. This speaker will continuously play the desired incident signal while the AFM is imaging a sample. The result is an image corrupted by the influence of the ambient noise. Some additional things to consider given this setup are the amplitude or volume of the incident signals and the secondary effects that may result from the initial signals reverberating with the microscope hood.

As depicted in Figure 2 above, the signal delivery system can be interpreted as the components of a linear system. However, although I know the AFM to be inherently nonlinear between modes, I will make this assumption to determine the magnitude of influence this nonlinearity has on resulting images. If the effects of audio signal interference have negligible difference between operating modes than this small signal model will hold; if not further investigation is required.

Incident Signals

The chosen incident signals that will be utilized for testing have been decided as follows:

- Impulse-like noise at periodic intervals
- Single frequencies ranging from 100Hz -20kHz
- Multiple frequency signals
- Complex music signals

The errors caused by the excitation of impulse-like noise will be representative of the system response in various modes. Single frequency incident signals will provide a basis by which I may compare the actual response of the system to expected results via convolution. Finally,

Sample Selection

Through my research and provided design requirements I determined that the two most likely candidates for the imaging sample would be PMMA acrylic or Lexan polycarbonate. Both have been used successfully for various forms of AFM lithography and have extremely flat surface characteristics [5]. In order to select the best candidate I imaged both and compared their average surface amplitude variance:

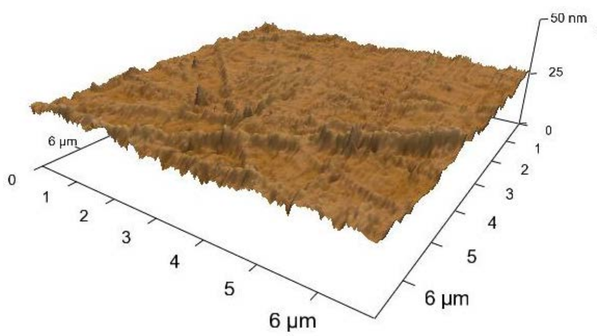


Figure 3: AFM Image – PMMA

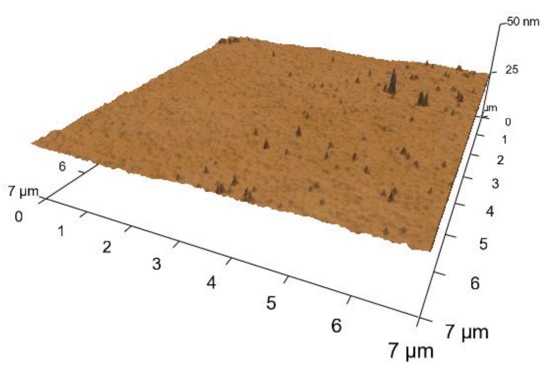


Figure 4: AFM Image - Lexan Polycarbonate

Based upon these results I have concluded that Lexan is the optimal choice for a sample material. The frequency content of its surface characteristics is very near 0 Hz, and initial lithography tests suggest it will be easily manipulated.

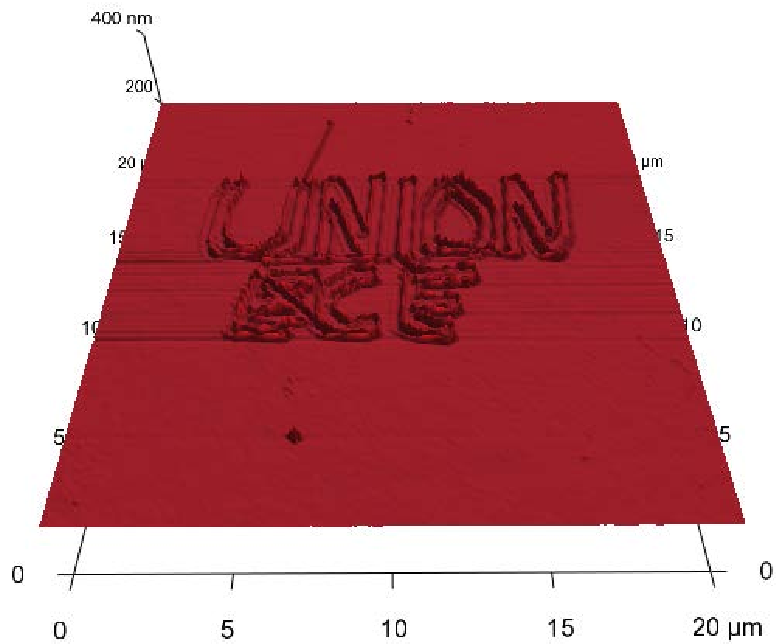


Figure 5: Preliminary Lithography Test (Scratching on Lexan)

Probe Tips

The proposed tip model for this project is the TAP300-Al, from budget sensors. According to my research this is the best, affordable hybrid tip that will work effectively in both contact and oscillating modes. Although it is categorized as primarily an AC mode tip, the aluminum coating make it much more durable that those without and thus usable in contact mode as well. Additionally, its resonance frequency is 300 kHz, well outside of the audible region.

Signal Processing Approach

The utilized signal processing will make use of both the IGOR software provided with the AFM, and MATLAB processes. IGOR will be used to level, scale and format the images appropriately. The newly formatted images will then be imported into MATLAB in the form of stacked arrays. Each array from the control image will be subtracted from each experimental image, leaving behind the data corresponding to noise induced error. If possible this data will be formatted back into an IGOR .ibw file for use in error characterization.

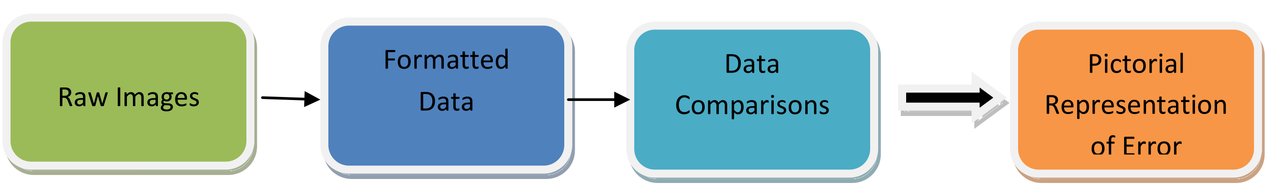


Figure 6: Image Processing Streamline

Final Design

Signal Delivery System

The final design of the signal delivery system did not differ much from the preliminary design. However, there were further component specifications that unearthed as testing began. Since a typical sampling rate of Union's Asylum Research AFM is around 1024s/sec, aliasing is to be expected over 512Hz according to the Nyquist rate. In practice however, one should aim to stay at least a magnitude of 5 – 10 below the Nyquist rate and because of this, the speakers utilized for this project require a very low frequency response. The selected speakers were rated down to 48Hz. The following components were utilized in the final signal delivery system design:

- Logitech Z313 Audio Speakers
    - Frequency Range: 48Hz – 22kHz
- Asylum Research MFP-3D Stand Alone AFM

Incident Signals

Impulse – Like

The impulse-like audio signal utilized was derived using Fruity Loops DJ software. The signal is a single snare drum beat with noise and decay manipulations. The utilized signal is shown below:

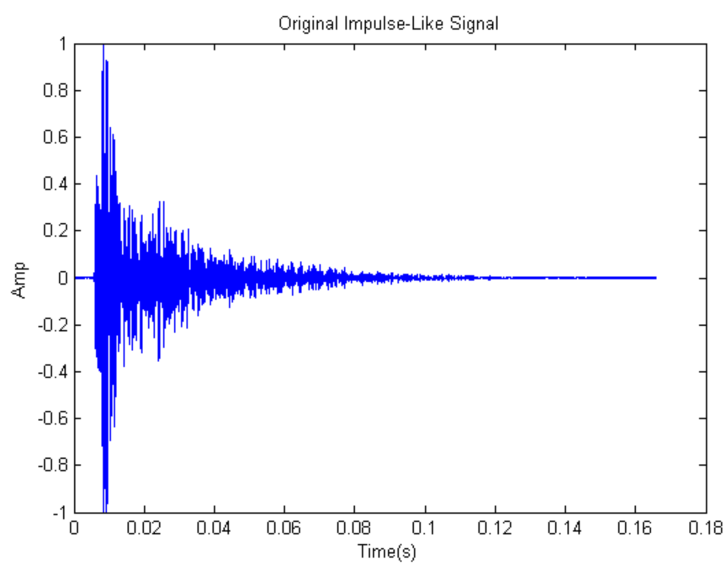


Figure 7: Utilized Impulse-Like Signal

Single Frequencies

All incident tones were created using Audacity open source software. Due to the relatively low sampling rate of the utilized AFM low frequency signals had to utilized to provide the best results. In an attempt to stay a magnitude of 5 below the Nyquist rate, a signal of 200Hz was used to excite the system for the purpose of the comparison between the three operating modes.

In order to investigate the extent of aliasing in the image errors frequency sweeps from 200Hz to 500Hz in 10Hz intervals were conducted. Additionally, several midrange frequencies from 1000Hz to 4000Hz were used to excite the system to determine the essential cut-off point at which audio signals did not have a noticeable effect on the imaging process.

Complex Signals

For the sake of accurate signal recovery a music signal with predominantly low frequency content was desired. The song settled upon was “Next Girl” by the Black Keys. This signal was delivered to the system in its original form as well as filtered through a low-pass filter with a cut-off at 500Hz. The filtered signal should minimize the effects of aliasing that would cause distortion in the recovered signal. The music signal in its original form is shown below:

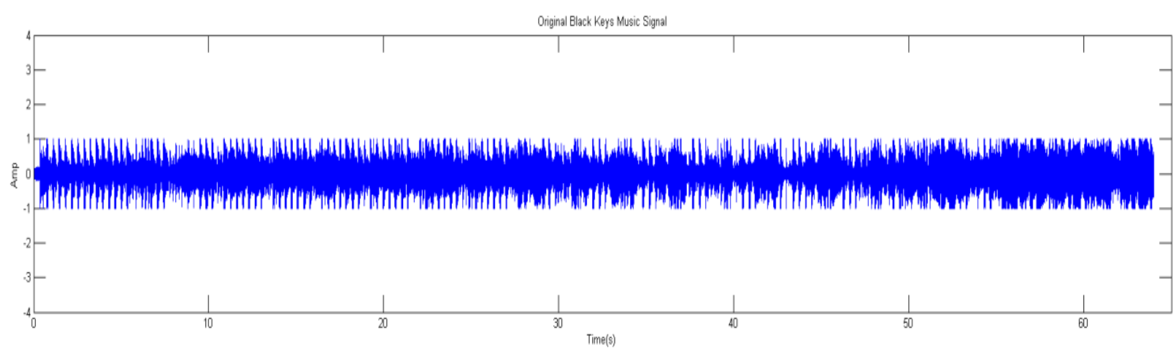


Figure 8: Original Incident Music Signal

Probe Selection

After further research the probes determined to be best suited for the purposes of this experiment were the model MULTI75AL probes, provided via Budget Sensors. These probes fit all of the outlined design specifications:

- Operates effectively in contact and non-contact modes
- Aluminum coating provides improved durability and reflective properties
- At $210 for a package of 10 this model is cost effective
- With a resonance frequency of 75kHz, there is no need to worry about over-stimulation from audio signals

Appendix B provides the product data sheet for the MULTI75AL probes.

Sample Material Selection

After preliminary imaging and lithographic tests, Lexan Polycarbonate was found to be the best suited material for the imaging substrate. This material met all outlined design specifications:

- Surface topography extremely flat (5nm variation on average)
- Capable of lithography for future purposes
- At $8 for a 8in by 12in section it is very cost effective

Two additional characteristics of Lexan that were observed during imaging are its vulnerability to surface charges and the difference in smoothness between sides. Often, surface charge resulted in greatly skewed and curved resultant images, and thus it is best to keep samples in a static proof bag or container. Also, I discovered that one side of the Lexan was covered in deep striations that caused difficulty when interpreting data. Once the smooth side was determined all samples were marked accordingly.

Data Processing Method

Leveling of images was automatically done via IGOR. Images were then saved in the form of delimited text and imported into MATLAB. Background subtraction was utilized to subtract the control or reference image from the experimental. Each row of an image data array was then concatenated to form a single line array, representative of audio information. De-convolution was originally attempted but found to be incredibly unreliable; another suggestion that the AFM system is not linear.

After image information was reorganized into a form that could be read as audio information, it was then subjected to filtering in an attempt to recover the incident signals. Although the filtering method varied from sample to sample, all were at least sent through a low-pass filter set at the appropriate Nyquist rate for the utilized sampling rate of the particular image. From that point a variety of noise reduction filters were applied in an attempt to determine an optimal method. The code for the background subtraction, concatenation and low-pass filtering is shown below:

```
function [ wave ] = AFMRECORD(Control, Exp)
a = Exp-Control;
e = magic(1);
for n = 1:64
    b = a(:,n);
    c = transpose(b);
    d = c(1,1025:1537);
    e =horzcat(e,d);

end

[x,y] = butter(10,.48813,'low');
f = filter(x,y,e);


wave = e;

end
```

Figure 9: MATLAB Code for AFMRECORD Function

The function AFMRECORD above may be manipulated to work for a variety of sampling rates and sample lines as determined in the imagine process.

A split filter, also commonly called an averaging filter was typically utilized for noise reduction. The code for such a filter used in the signal processing portion of this project is shown below:

```
function [ Y ] = SPLITF( F )

L = size(F,2);
b = magic(1);
for n = 3:L-3;
    a =  (F(1,n)  + F(1,n-1)  + F(1,n-2)+F(1,n+1)+F(1,n+2))/5;
    b = horzcat(b,a);
end

Y =b;

end
```

Figure 10: Noise Reduction Filter Code

By averaging every five concurrent points in the image data, the peaks were accentuated and the noise primarily caused by the variance of the sample surface, was minimized.

Implementation & Results

Impulse Response of Different Modes

The impulse-like audio signal shown in Figure 7 was used to excite the AFM system while imaging in three different operating modes; attractive, repulsive and intermittent. The resulting impulse responses of the system in each mode are shown below:

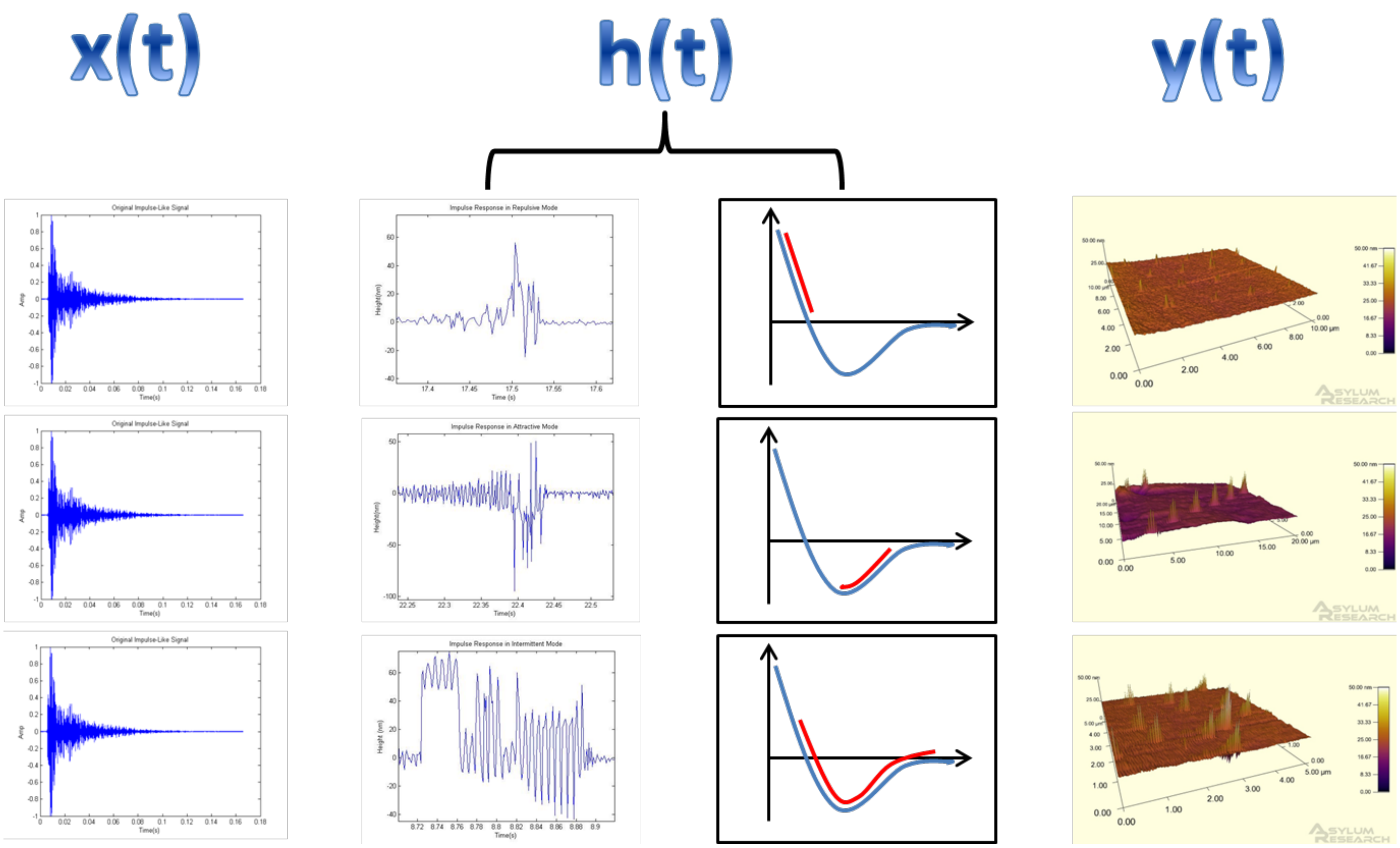


Figure 11: Impulse Responses in Three Different Operating Modes

In Figure 10 above, the top row illustrates repulsive mode impulse response, the middle row attractive, and the bottom row intermittent. These results are shown in greater detail in **Appendix C**. What one should observe about these images is the great difference in the impulse response between modes of the AFM. The impulse response is found to be shortest and least complex in repulsive mode and the longest and most complex in intermittent mode.

Single Frequency Incident Signal Response

With the approximate impulse response of each operating mode determined, I am now able to compare the experimental results of excitation with frequency signals to expected results using the theory of convolution.

Repulsive Mode

Using convolution and the previously determined impulse response of the repulsive mode, the following experimental and expected results were determined for a 200Hz incident signal:

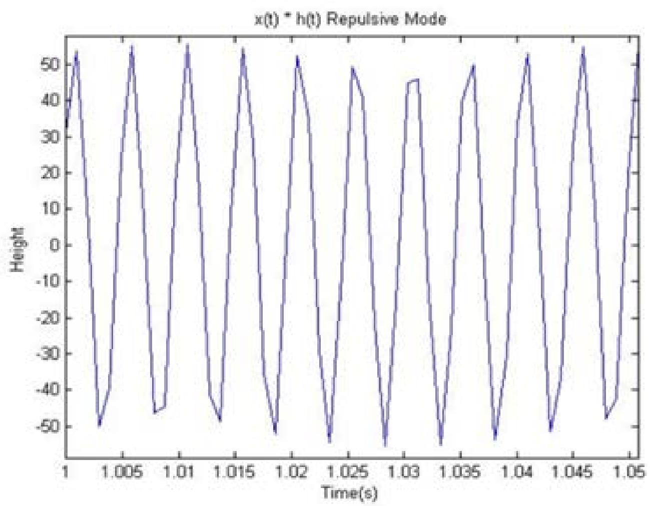


Figure 12: Expected Response to 200Hz Incident Signal; Repulsive Mode

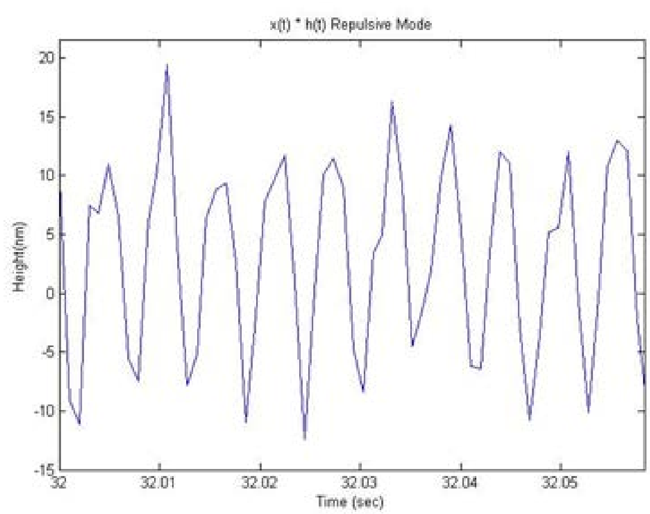


Figure 13: Actual Response to 200Hz Incident Signal; Repulsive Mode

Several conclusions can be drawn from these results. First and most importantly, the difference in shape of the two curves suggests that even within a single mode the small signal model does not hold; that is to say that one cannot assume linearity in repulsive mode despite the fact that it operates within a fairly linear regime on the force curve in Appendix A. Furthermore, a frequency analysis of the experimental results yields an approximate frequency of 178Hz. This is a clear indication of aliasing even though 200Hz is well below the Nyquist Rate.

Intermittent Mode

The same comparison as before was then done in intermittent contact mode. Results using a 200Hz incident signal are shown below:

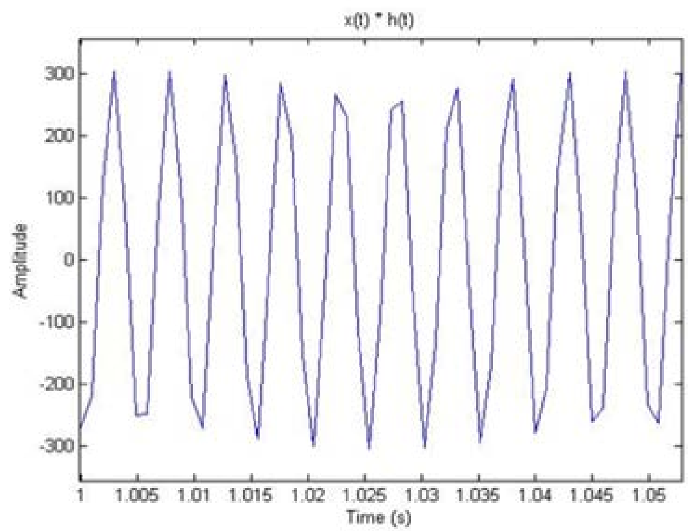


Figure 14: Expected Response to 200Hz Incident Signal; IC Mode

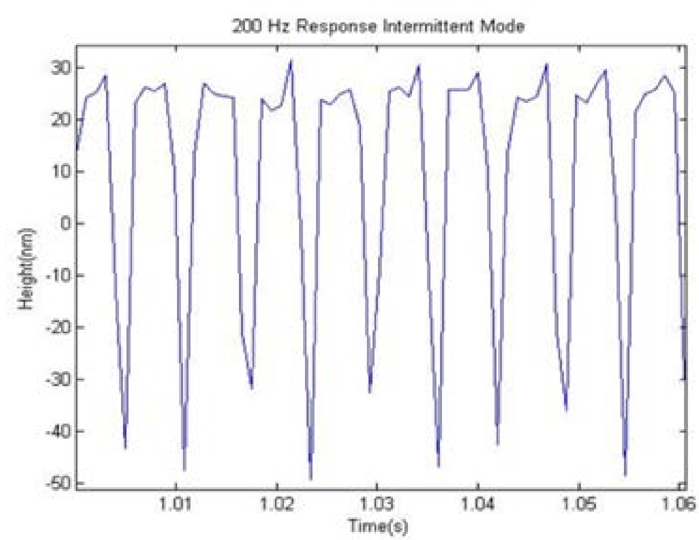


Figure 15: Actual Response to 200Hz Incident Signal; IC Mode

Similarly, these results have shown that a small signal model does not hold in intermittent contact mode as well. One particular criticism of the results shown in Figure 13 however, is the apparent clipping of the top portion of the sinusoidal curve. This could very well be caused by an offset of the sampling rate and the phase of the incident signal. Although reimaging is necessary to confirm or deny this hypothesis, considering how much more complex the impulse response of intermittent mode is than repulsive I deduce that the prior results would still hold.

Effects of Aliasing

Despite the attempts to conduct this investigation using frequencies well below the Nyquist rate, aliasing was still present and quite obvious in results. Further investigation is required to properly characterize the effects of aliasing; however frequency sweeps were conducted to gather a general idea of the extent of the aliasing. The image below depicts the results of one such sweep:

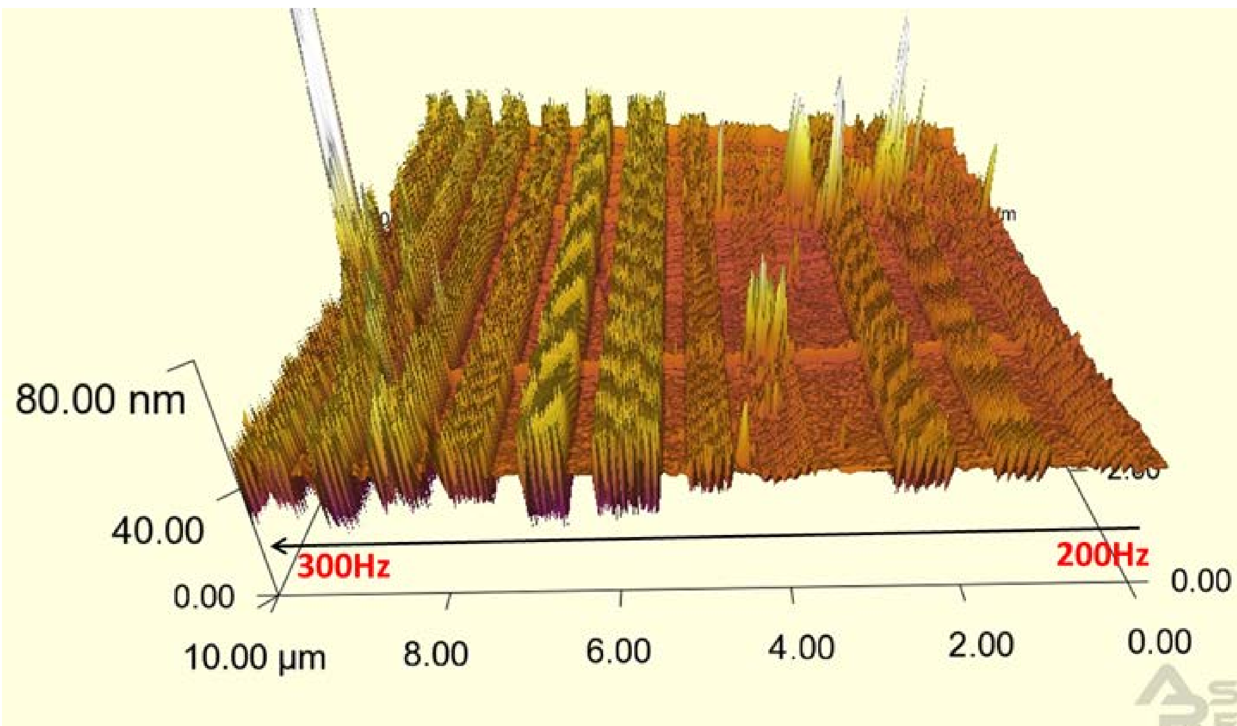


Figure 16: Frequency Sweep from 200Hz to 300Hz in 10Hz Intervals

The relationship between amplitude and frequency in the above image leads me to assume that the effects of aliasing are quite severe despite operating 2 to 5 times below the Nyquist rate.

Amplitude Analysis

Another method by which one can estimate the extent of the nonlinearity of a system is by the analysis of the effect that the amplitude of an incident signal has on the output of the system. To investigate this, I utilized attractive mode and excited the system with the same impulse with varying amplitudes. The results of one such experiment are shown below:

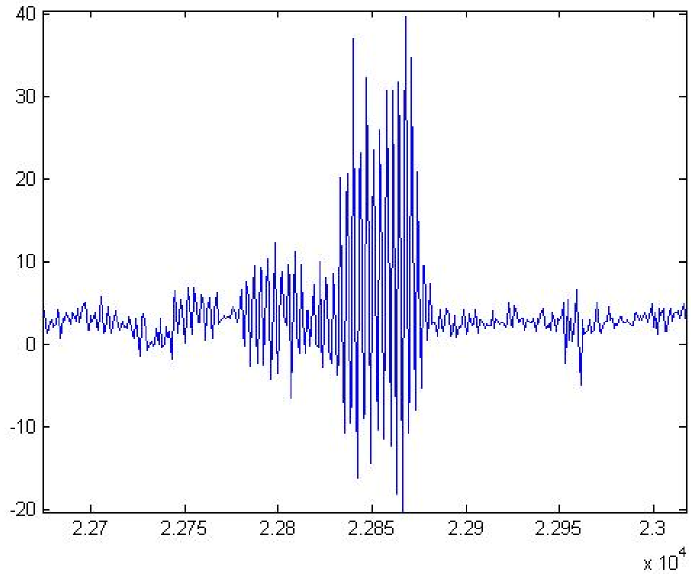


Figure 17: Amplitude Test Attractive Mode; Amp = x

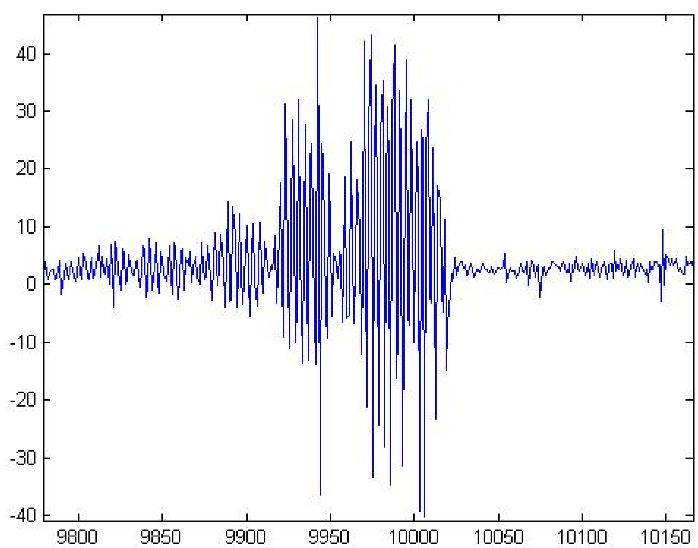


Figure 18: Amplitude Test Attractive Mode; Amp = 2x

The amplitude of the impulse response of the original signal was measured to be approximately 59nm at its maximum. The amplitude of the second impulse response, in which the incident signal had amplitude twice the original, was 86nm. If this system were in fact linear, we would expect that a magnitude 2 change in amplitude of the incident signal would yield a magnitude 2 change in the output signal; this experiment suggests yet again that this is not the case. Although the increase in amplitude of the incident signal did increase the amplitude of the output signal, it was only by a factor of 1.46, not 2 as desired. Running the same test in repulsive and intermittent modes as well would help determine which mode is most linear and which is least linear.

Recovery of Music Signals

Using the images produced in the presence of musical incident signals shown in **Appendix D**, attempted recovery of the incident music signal shown in Figure 8 resulted in the following waveform:

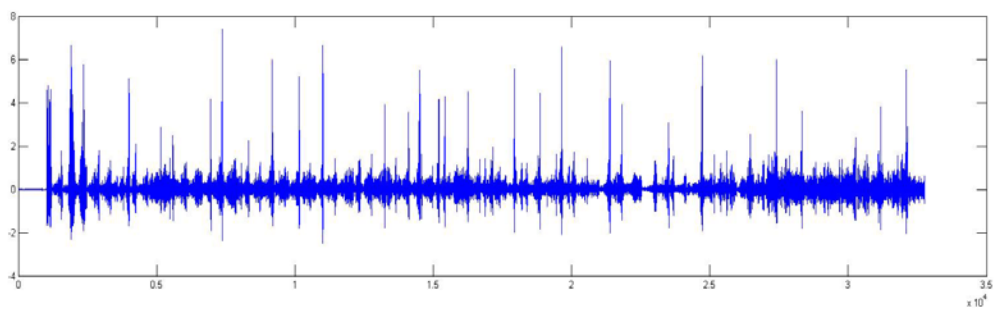


Figure 19: Recovered Waveform of Music Signal

Although the resultant waveform above, looks and sounds nothing like the original incident signal, I argue that it is however highly differentiable from the typical noise caused by the sample surface. What this suggests is that although the effects of aliasing have greatly distorted the incident signal through the AFM system, some components of the signal are still present, but muddled.

Another complication besides aliasing in recovering non-periodic signals is caused by the method in which the AFM images. The Asylum Research AFM traces each line of the scan area twice. Although this retrace allows the user to identify whether or not the resultant image is accurate, it essentially causes the loss of every half period of the operating scan rate. That is to say if imaging with a 1Hz scan rate, every half second of the music second is not imaged.

Conclusions:

The results of this scientific investigation have led to the following conclusions:

- Effects of non-linearity between operating modes of an AFM are not negligible
- The system response within a single mode has been shown to be non-linear
- It is possible to recover approximate periodic audio signals from AFM imaged via digital signal processing
- Aliasing within the designed system begins to occur well below the Nyquist rate

Each mode of operation produced a different impulse response. The shortest response was found in repulsive mode; the longest in intermittent contact mode. This is qualitatively consistent with the non-linear characteristics of the force-distance curve, however the implications of these differences proved to be more than negligible.

The fact that non-linearity between AFM modes is non-negligible should be a paramount concern for almost every AFM user. Although most users are aware of the non-linear force-distance relationship, it is very common to switch freely between AFM modes. Often users may utilize attractive mode simply to preserve the apex of the probe tip and thus save money, however one should now consider the implications of such decisions. Since different modes yield different results, so too must the interpretation of said results differ.

Convolution of incident sinusoids excitations with the measured impulse responses produced results that resembled the measured output, yet contained noticeable differences. Differences were also observed in the images obtained in the three modes for a music signal excitation. This implies that a “small signal” linearized model was not valid for the experimental parameters chosen.

On the whole, it is of great interest to an AFM user to know when a “small signal” model is valid or not. The results of this investigation have introduced a unique method of probing an AFM system in order to identify these points. What has been established thus far is a concrete proof of concept for this analysis method as well as several key foundations on which to build and move forward.

Future Work:

From this point in the investigation of the effects of ambient noise on the AFM imaging process, there are countless opportunities for continued research. The most obvious and practical of which being a more thorough analysis and description of the differences in between attractive, repulsive and intermittent imaging modes. A better understanding of these differences will essentially lead to an improved methodology for interpreting image errors produced in all modes of operation.

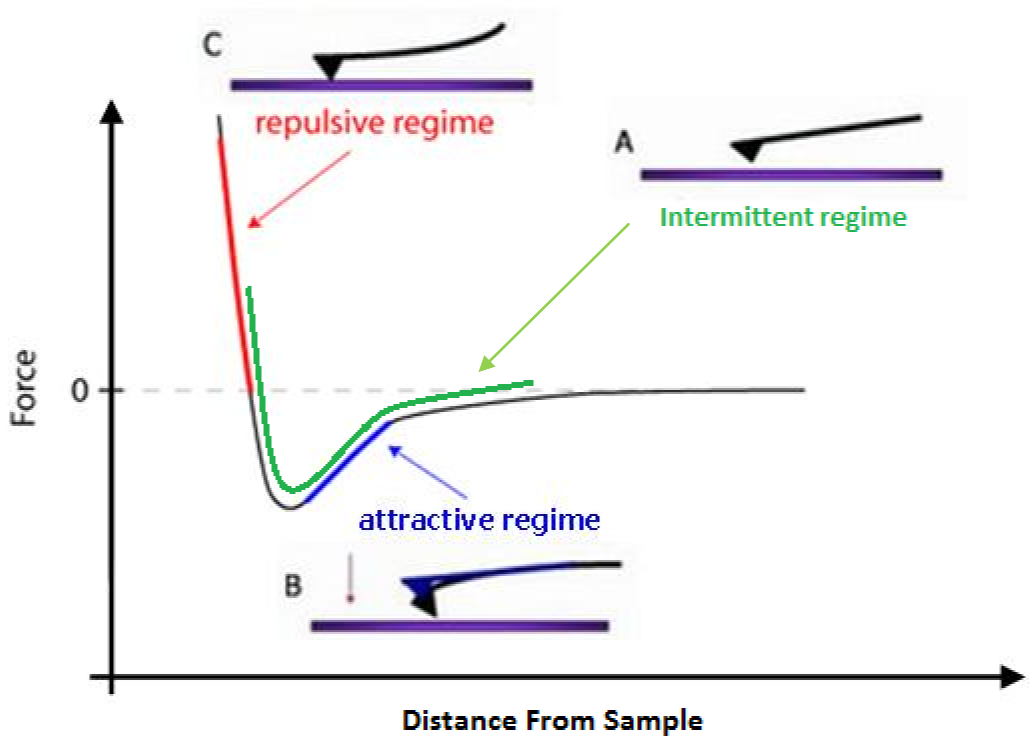
Additionally, the effects of aliasing could be better understood with wide range frequency sweeps and their analysis. Similarly, I would very much like to be able to better describe the effects of amplitude on error characteristics. These are two areas of this study that can be relatively easily researched and the results would be extremely valuable.

The most exciting path I would like to see this project take is to continue on the route towards successful music signal recovery and mimicking of such errors through lithography. The idea of encoding music into an image would be a tremendous combination of science and art. In order to get there however, several drastic changes to the system must be made:

- Increased, accurate sampling rate of AFM (10K minimum)
- Better performance speakers
- Ability to image in less sensitive regime (removal of mode complications; uni-modal system)
- Utilization of photo-resist or other lithography methods
- Single trace of scan area

The development of such a system under these guidelines would make it much more possible to encode and recover complex musical signals.

Appendix A: Generic AFM Force-Distance Curve



A) In intermittent contact mode the system is actually switching rapidly between attractive and repulsive modes, resulting in and average force of 0N acting on the cantilever.

B) Attractive mode occurs when the probe is further from the sample surface, resulting negative force acting on the cantilever, pulling it towards the sample surface.

C) Repulsive mode occurs when the probe is closer to the sample surface, resulting in positive force pushing the cantilever away from the sample surface.

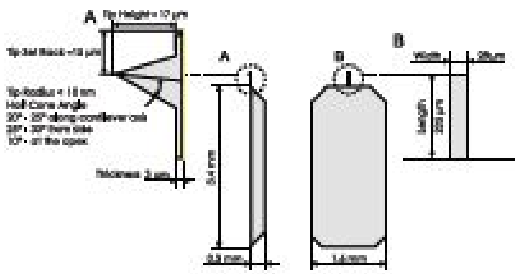
Curve adapted from content on < http://www.ism.cnr.it/english/linee/MD.P06.006.php>

Appendix B: MULTI75AL Probe Data Sheet

BudgetSensors

AFM probe Model: Multi75Al

- Force Modulation, Pulsed Force Mode (PFM)
- Rotated Monolithic Silicon Probe
  Symmetric Tip Shape
  Chipsize: 3.4 x 1.6 x 0.3 mm
- Coating: Aluminium reflex coating, 30 nm thick
- This probe uses an "on scan angle" symmetric tip to provide a more symmetric representation of features over 200 nm.



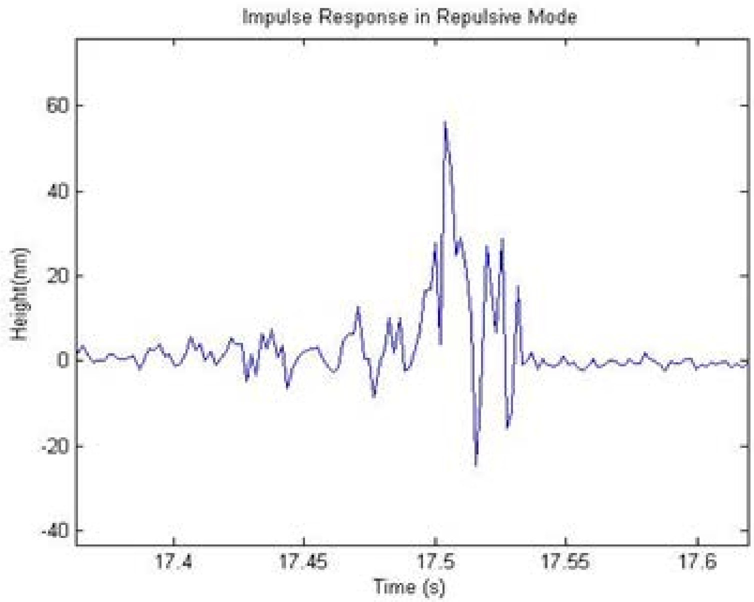
	Typical Values	Range
Resonant Frequency	75 kHz	+/- 15 kHz
Force Constant	3 N/m	1 - 7 N/m
Cantilever Length	225 µm	+/- 10 µm
Mean Width	28 µm	+/- 5 µm
Thickness	3 µm	+/- 1 µm
Tip Height	17 µm	+/- 2 µm
Tip Set Back	15 µm	+/- 5 µm
Tip Radius	< 10 nm	
Coating	30 nm thick Aluminium coating	
Half Cone Angle	20º - 25º along cantilever axis 25º - 30º from side 10º at the apex	

Order Code	Units in Package	Coating	Price
Multi75Al-10	10 pieces	Aluminium Reflex	$210
Multi75Al-50	50 pieces	Aluminium Reflex	$890
Multi75Al-W	380 pieces	Aluminium Reflex	$3900

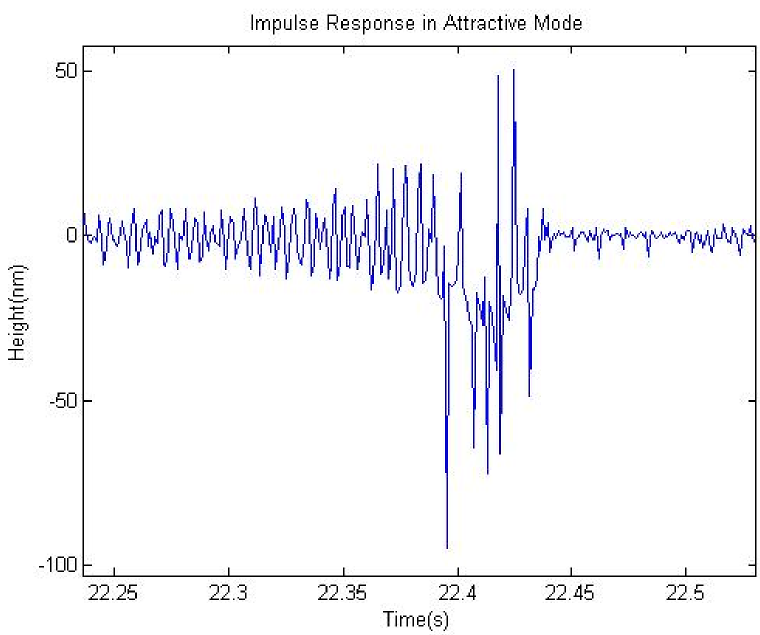
www.budgetsensors.com

Appendix C: Impulse Responses of Different Modes

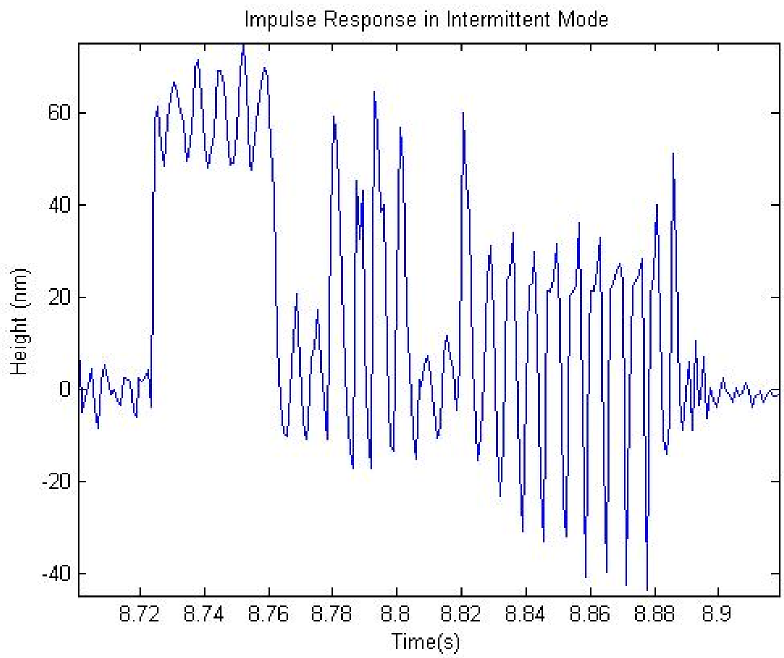
Repulsive Mode:



Attractive Mode:

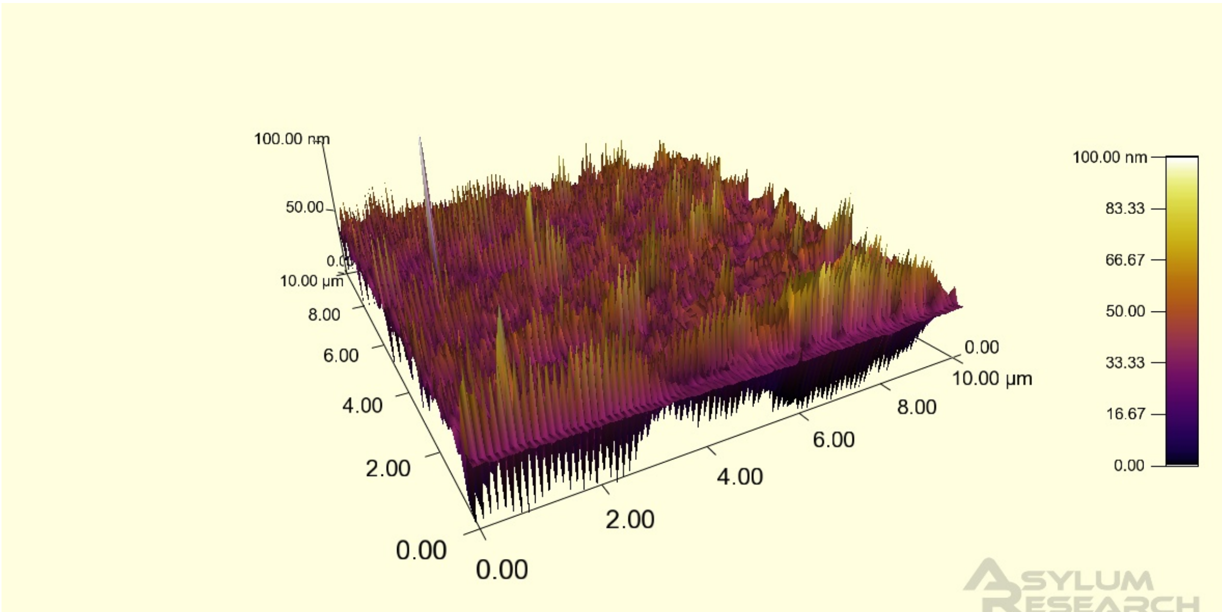


Intermittent Mode:

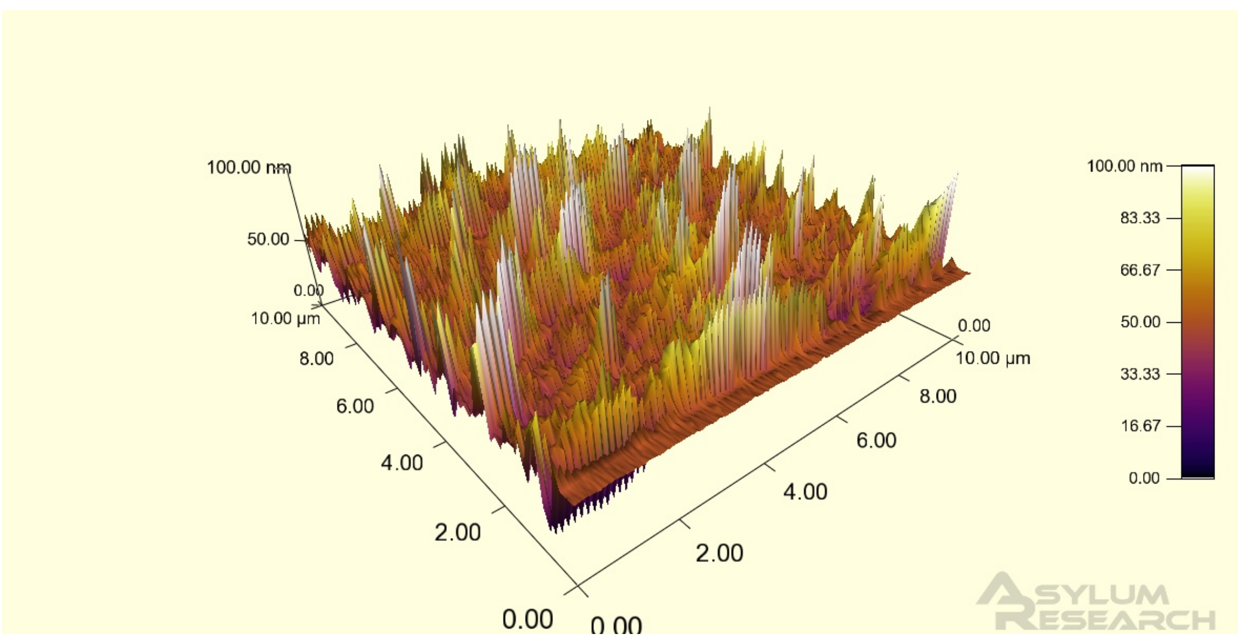


Appendix D: Music Signal Images

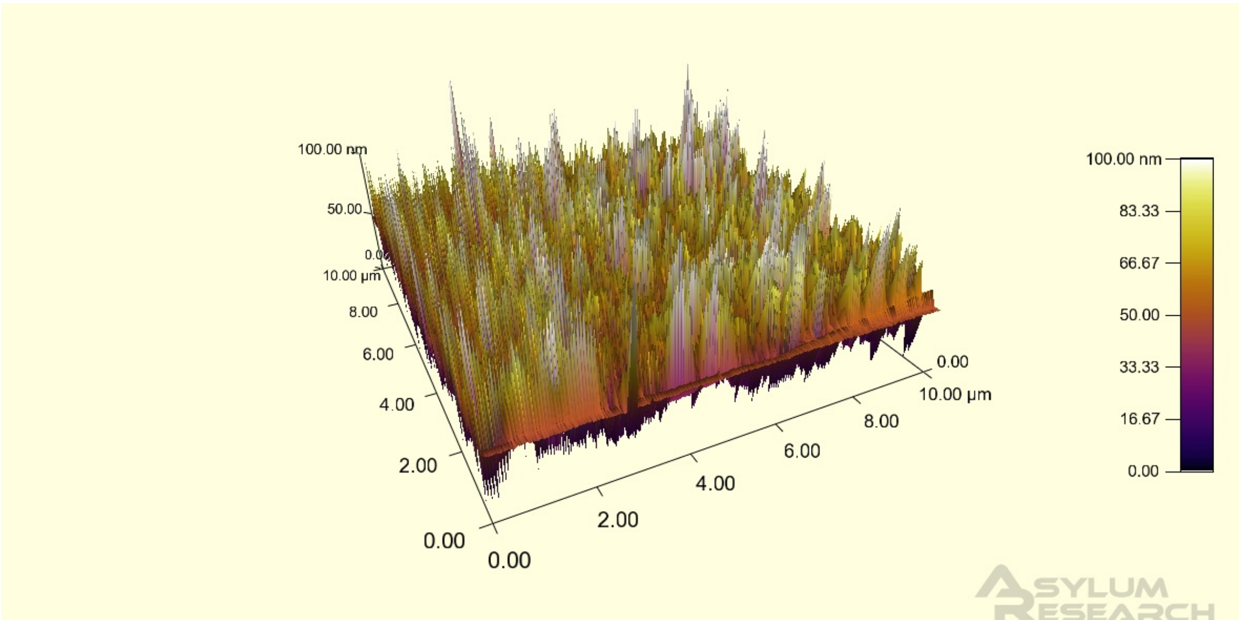
Repulsive Mode:



Intermittent Mode:



Attractive Mode:



**All images were taken over the same scan area of a single sample. The repulsive mode and intermittent mode images utilized a sampling frequency of 1024Hz, and the attractive mode 2048Hz.

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[1] E. Eleftheriou, T. Antonakopoulos, GK Binnig, G. Cherubini, M. Despont, A. Dholakia, U. Duerig, M.A. Lantz, H. Pozidis, H.E. Rothuizen and P. Vettiger, Millipede-A MEMS-based scanning-probe data-storage system. IEEE Transactions on Magnetics, Vol. 39, No. 2, p938, 2003.

[2] Fadeyev, Vitaliy; Haber, Carl; Maul, Christian; Mcbride, John W.; Golden, Mitchell Reconstruction of Recorded Sound from an Edison Cylinder Using Three-Dimensional Noncontact Optical Surface Metrology. Lawrence Berkeley National Laboratory, Berkeley, CA, USA; JAES Volume 53 Issue 6 pp. 485-508; June 2005

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[4] Russ, J. C.,Correcting Image Defects. In *The Image Processing Handbook* fifth edition. CRC: 2006; pp 195 – 268.

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